Neutrinoless double beta decay: the nuclear structure ingredient *

B. P. Kay
Brown-bag seminar, Wednesday 19 Nov., 2008

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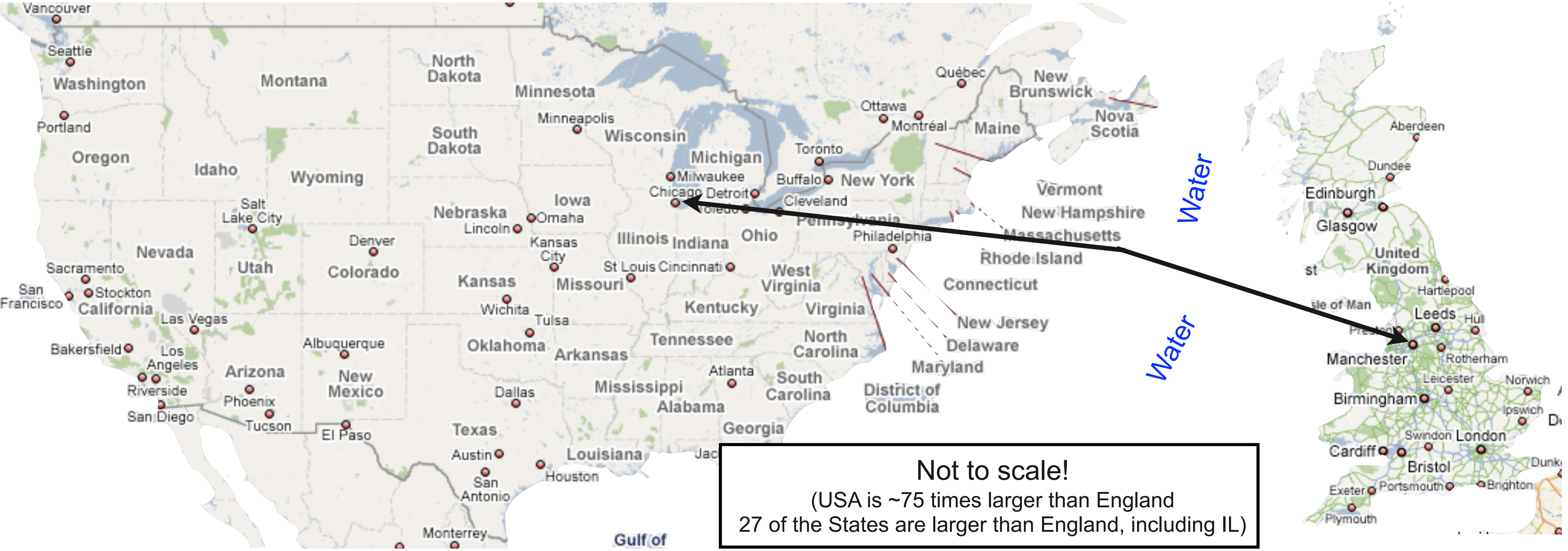
*This work is supported by the US Department of Energy, Office of Nuclear Physics, under Contract Nos. DE-FG02-91ER-40609 and DE-AC02-06CH-11357, the UK Science and Technology Facilities Council, the IN2P3 / CNRS-France and the German BMBF.

Mini autobiography (Giselle normally asks for one!)

- 1981, born, near Manchester,
- Stayed there for 26 years,
  - 2000-2004: BSc and Masters degree at the University of Manchester,
  - 2004-2007: PhD at the University of Manchester,
- 2007-present, Argonne National Laboratory, Illinois, USA,
  - Subject of choice: experimental nuclear-structure physics.

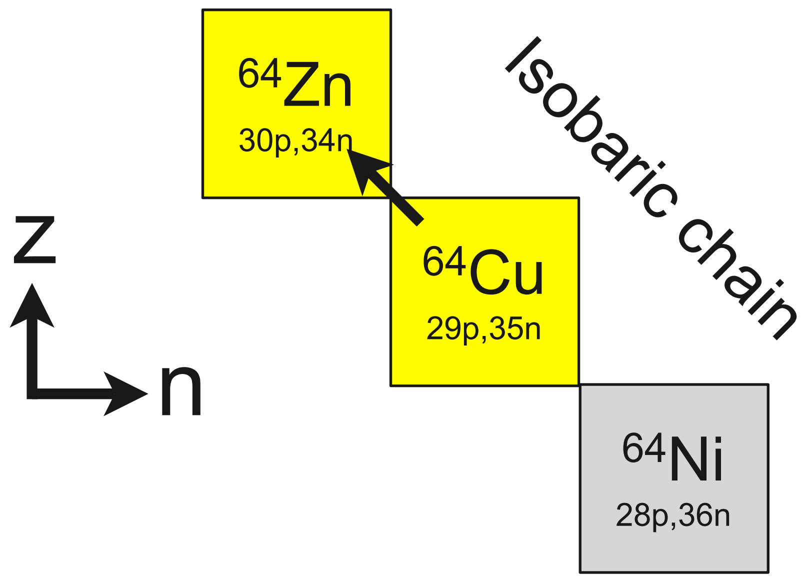


Outline

- The hypothesis that is neutrinoless double beta decay (some background first)
- Nuclear matrix elements, their importance and the problem
- An experimentalists rationale
- How we access the numbers we want: tools of the trade
- A series of experiments
- The final picture, and also a slight shrug of the shoulders (our results require some interpretation by the community)

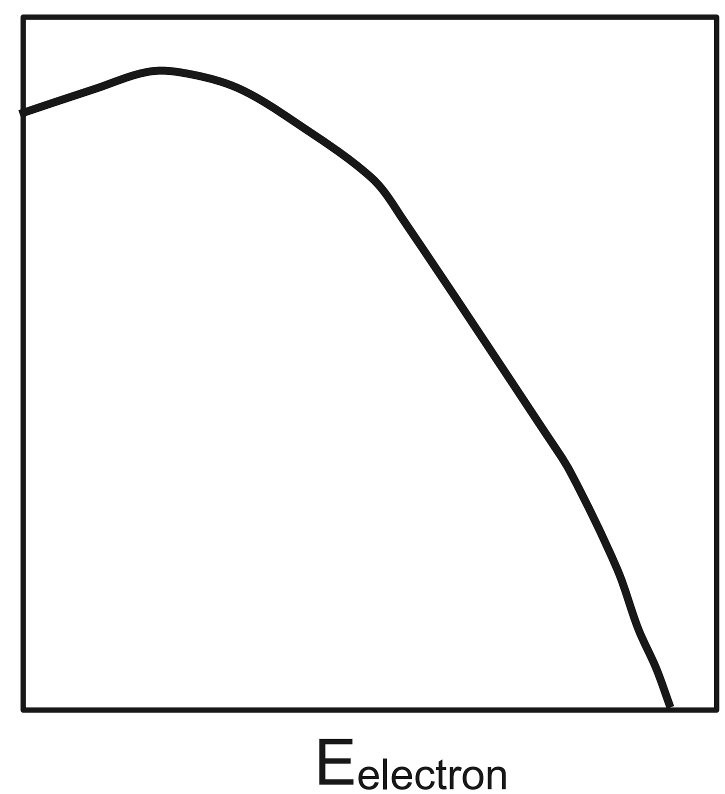
Beta decay and neutrinos (the 'small neutral ones')

- *Beta decay is the most common form of radioactive disintegration:*
  - β^- decay, emission of an electron (e^-) and an antineutrino ($\bar{\nu}$),



β^- decay:

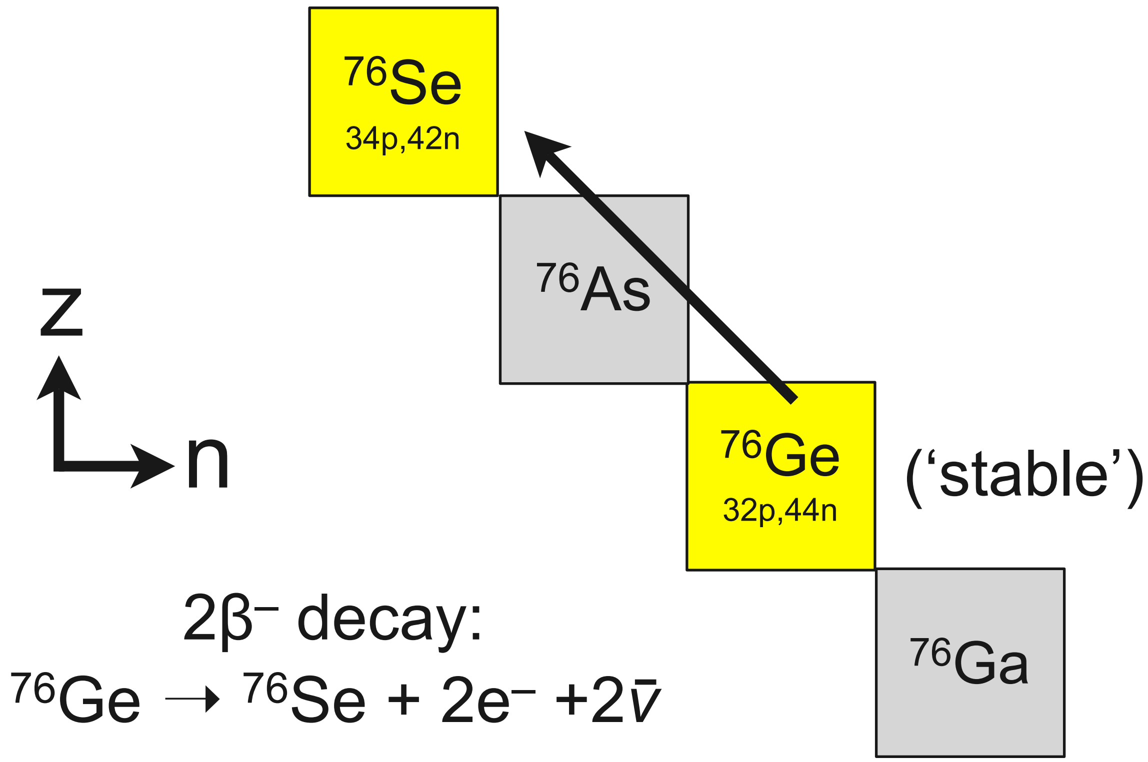
$$^{64}Cu \rightarrow {}^{64}Zn + e^- + \bar{\nu}$$

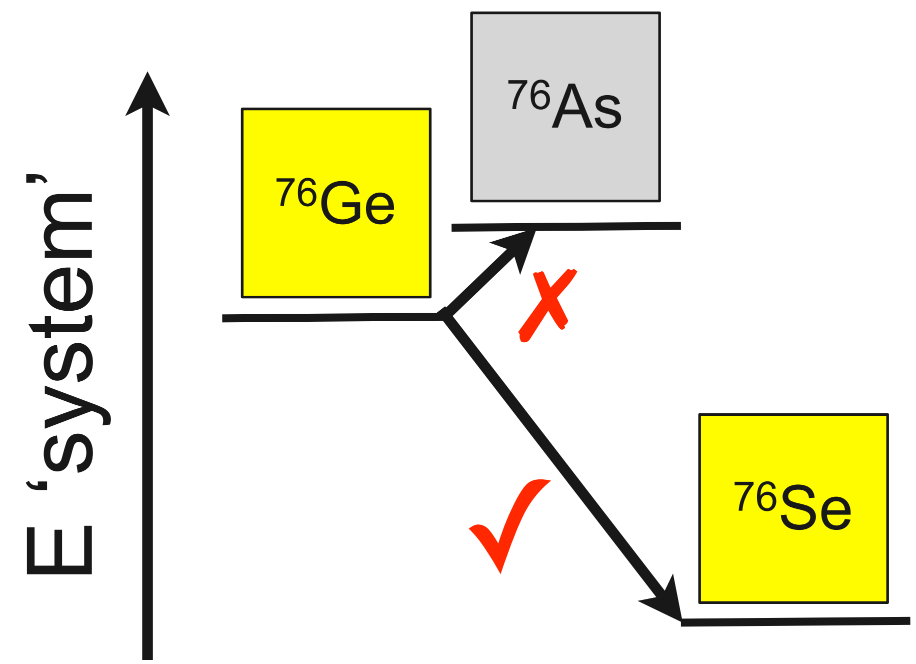


- *The neutrino came about because of the electron energy distribution for beta decay is continuous – W. Pauli proposed a second particle present [1934], later named the neutrino by E. Fermi [1934]. More about the neutrino in a few slides.*

Double beta decay with neutrinos

- Ordinary beta decay in heavier nuclei can be energetically forbidden (or strongly, strongly prohibited), however a simultaneous emission of two beta particles is not: double beta decay. E.g.

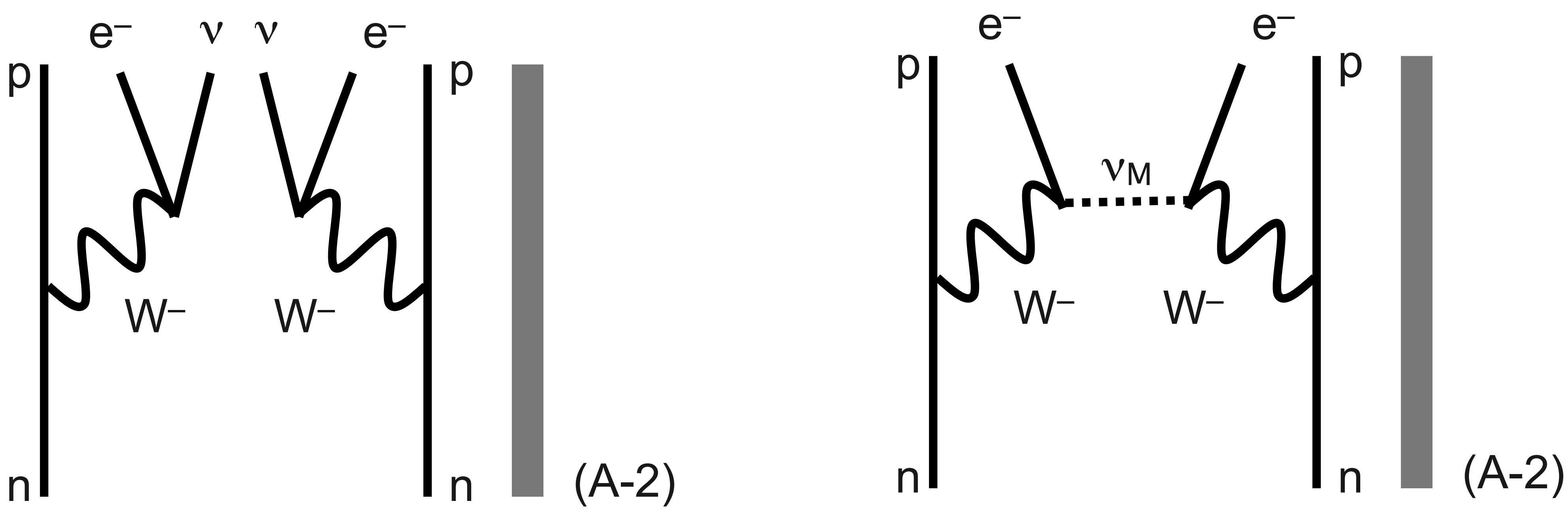




- This has been observed in several isotopes, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{150}Nd, etc.

- The half lives are incredibly long: ~10^{19} years and longer

Double beta decay without neutrinos – a long-standing hypothesis based on E. Majorana's neutrino thoughts



✓ e.g. $^{76}Ge \rightarrow {}^{76}Se + 2e^- + 2\bar{\nu}$

? e.g. $^{76}Ge \rightarrow {}^{76}Se + 2e^-$

- They are several proposed candidates for this (is it energetically possible)
- Half-life estimates are ~10^{22} years and greater
- Why is this so exciting?

Neutrinoless double beta decay

- Neutrinoless double beta decay, if observed, would prove neutrinos are their own antiparticles, differing only by their helicity

  (Majorana's hypothesis from the 1930's)

- Observation could provide the first determination of the neutrino mass if the nuclear matrix elements known

- Is lepton number conserved? No! unless 'new physics'

  (Standard-Model-of-Particle-Physics consequences)

- Intense efforts (and investments) are under way in search of this decay process

  (Majorana ^{76}Ge, Cuore ^{130}Te, EXO ^{136}Xe, GERDA ^{76}Ge, NEMO Mo,Se, Heidelberg-Moscow ^{76}Ge)

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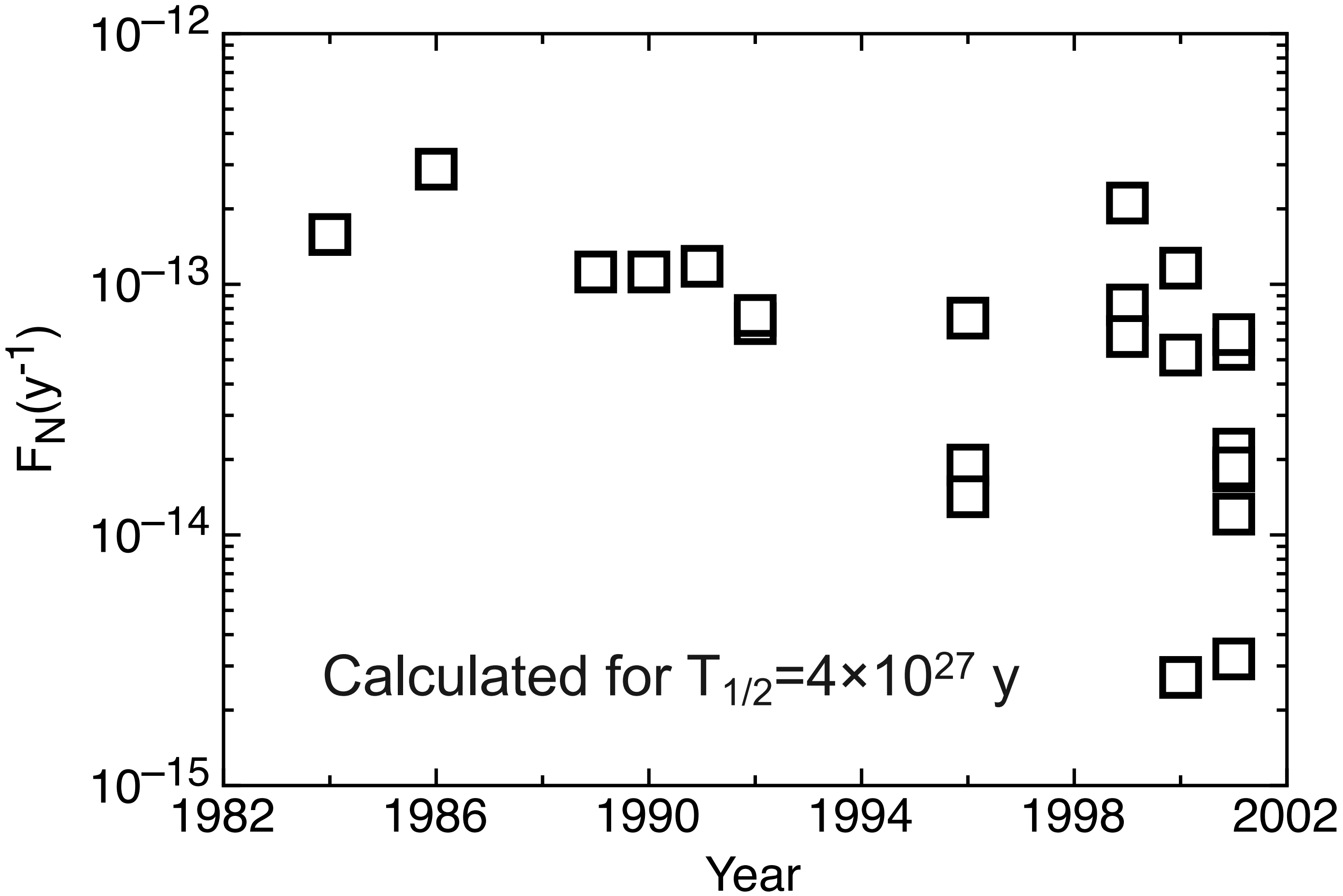
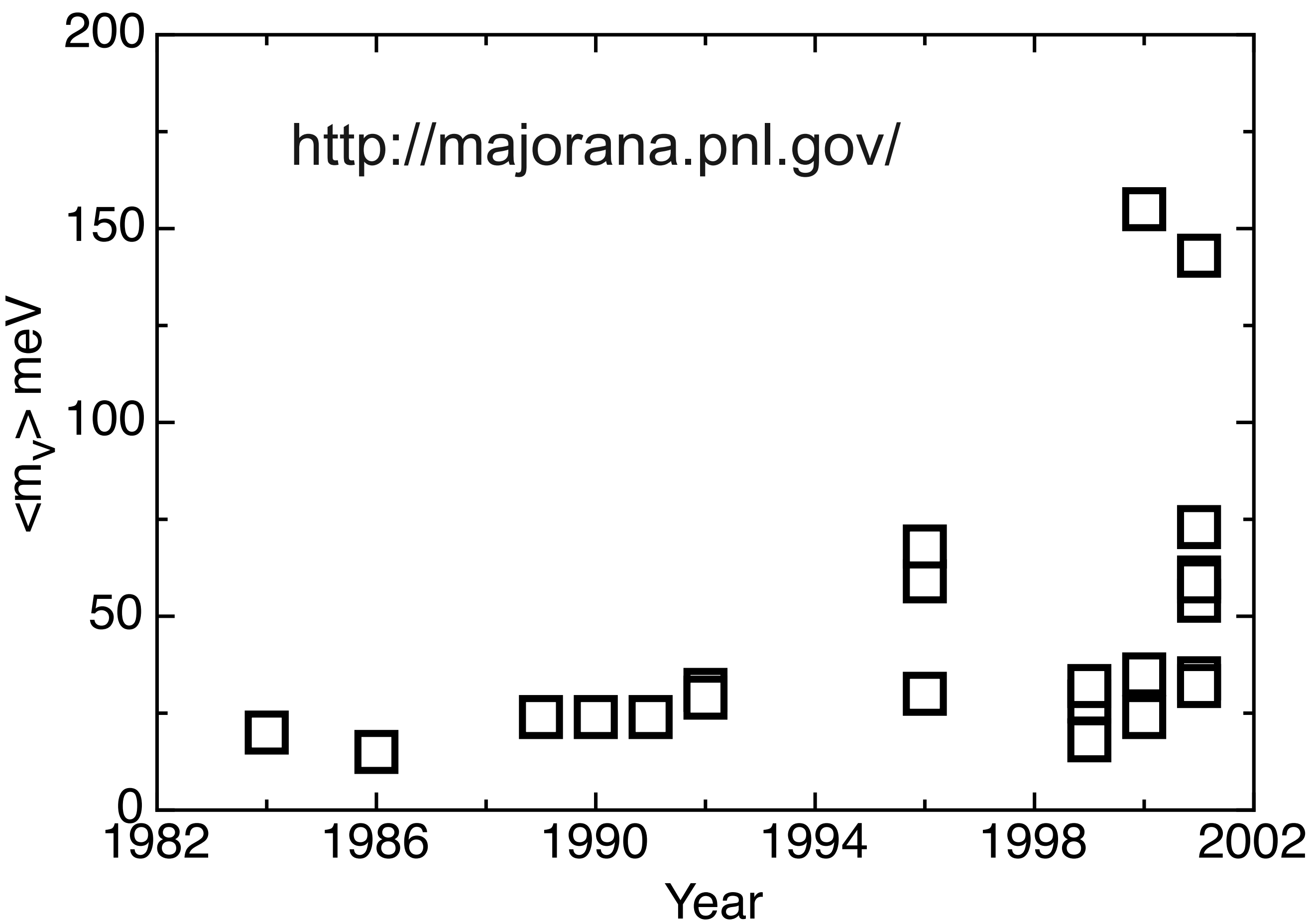
"The uncertainty in the calculated nuclear matrix elements for neutrinoless double beta decay will constitute the principle obstacle to answering some of the basic questions about neutrinos"

–– J. Bahcall PRD 70, 033012 (2004)

- In this work we take an experimentalist nuclear-physicists view on this and ask what we can do to address this uncertainty. Our focus: ^{76}Ge,^{76}Se

Nuclear matrix elements (low on detail)





Rate = *nuclear matrix element* * *expectation value of the neutrino mass*

If observed, this is known

Theoretical calculations (a problem)

The Holy Grail (with small error bars, please)

An experimentalists' rationale

Needs

- There ***has*** to be a firm calibration of nuclear theory against measured properties of nuclear structure but…

Problem

- …there is no suitable reaction that would simply resemble the n.m.e.'s for $0\nu 2\beta$ (e.g. double charge-exchange reactions are complicated multi-step processes)

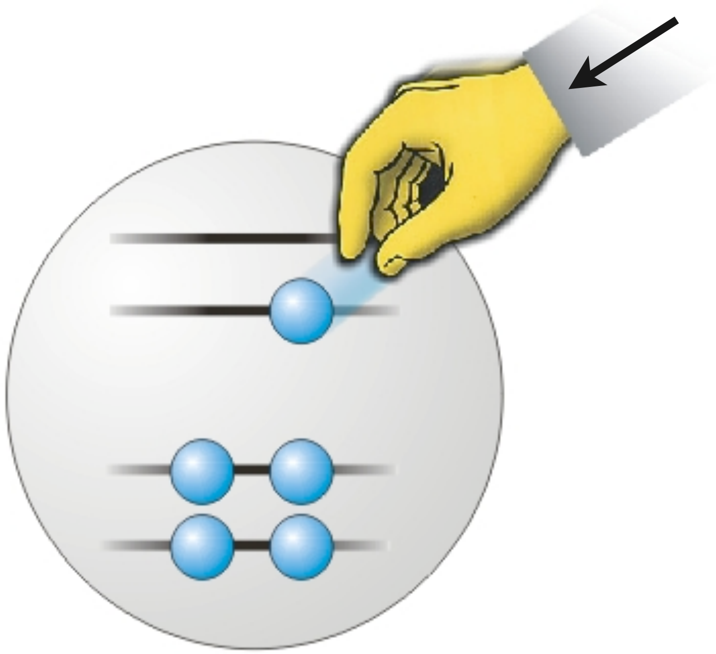
Our rationale

- Ultimately, the process must depend on the ***overlap between the initial and final ground state wave functions***...

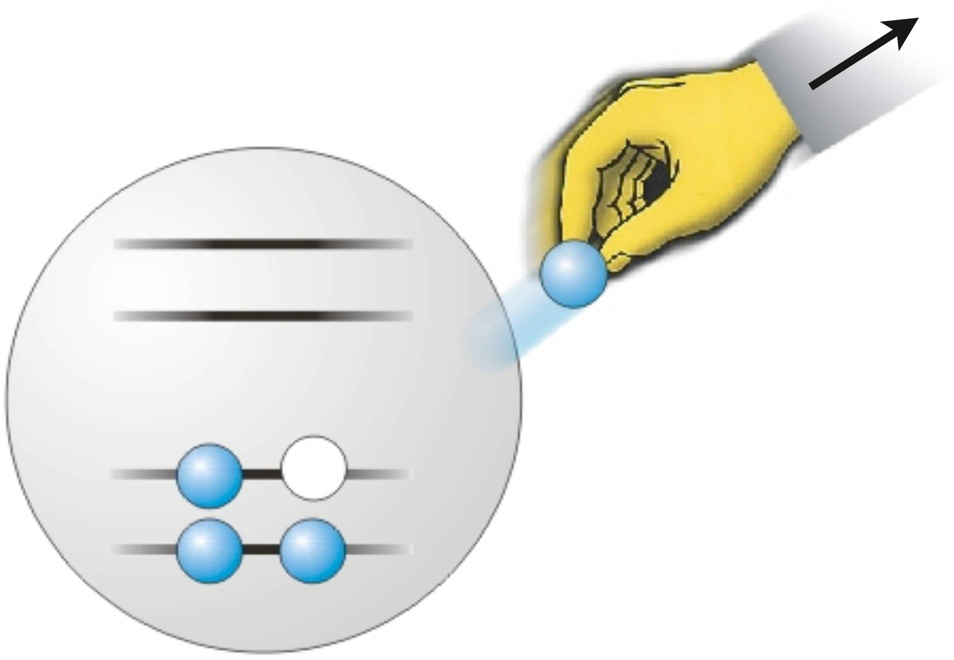
- Ingredients of the wave functions include how many / how few protons or neutrons exist in the ground states of parent and the daughter – ***we can measure this using single-nucleon transfer reactions***

Single-nucleon transfer

- Single-nucleon *ADDING* probes the *EMPTINESS* of the orbital, or the vacancy
  - (cross section proportional to how many ‘places’ available in the orbital)



- Single-nucleon *REMOVAL* probes the *FULLNESS* of the orbital, or the occupancy
  - (cross section proportional to how many particles that are in the orbital)

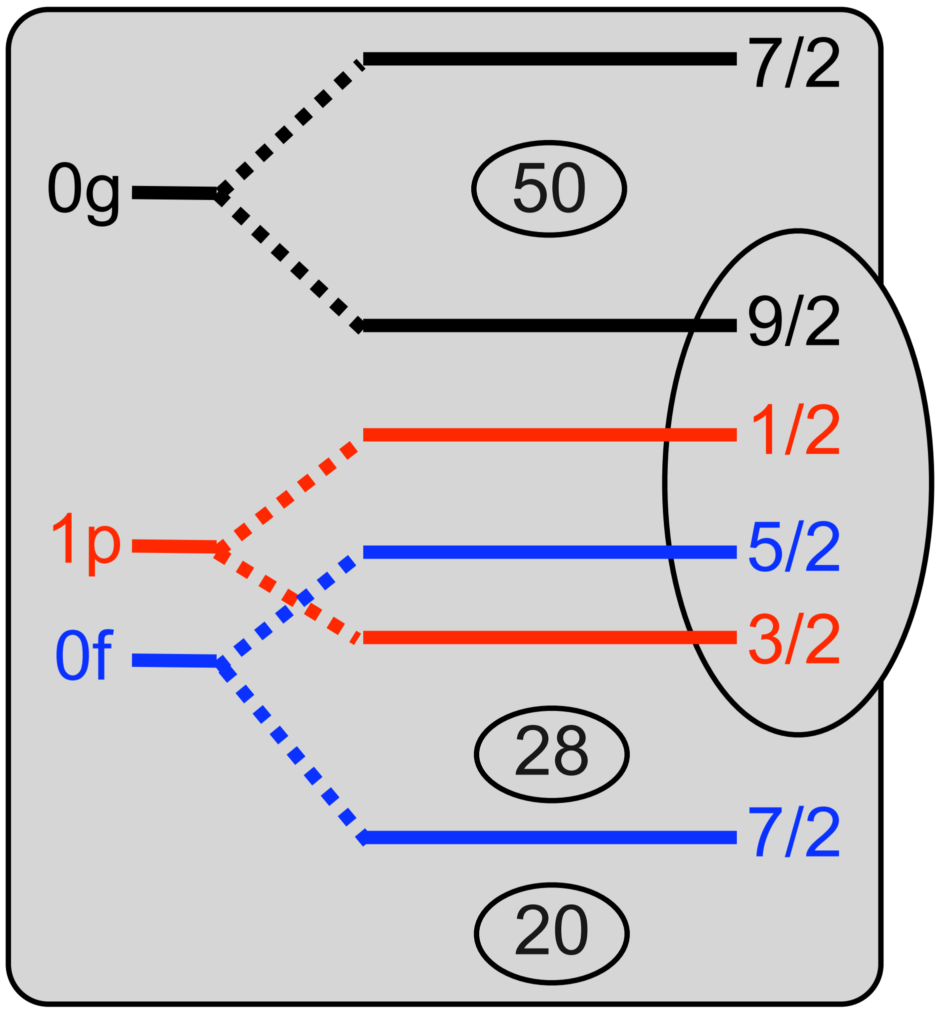


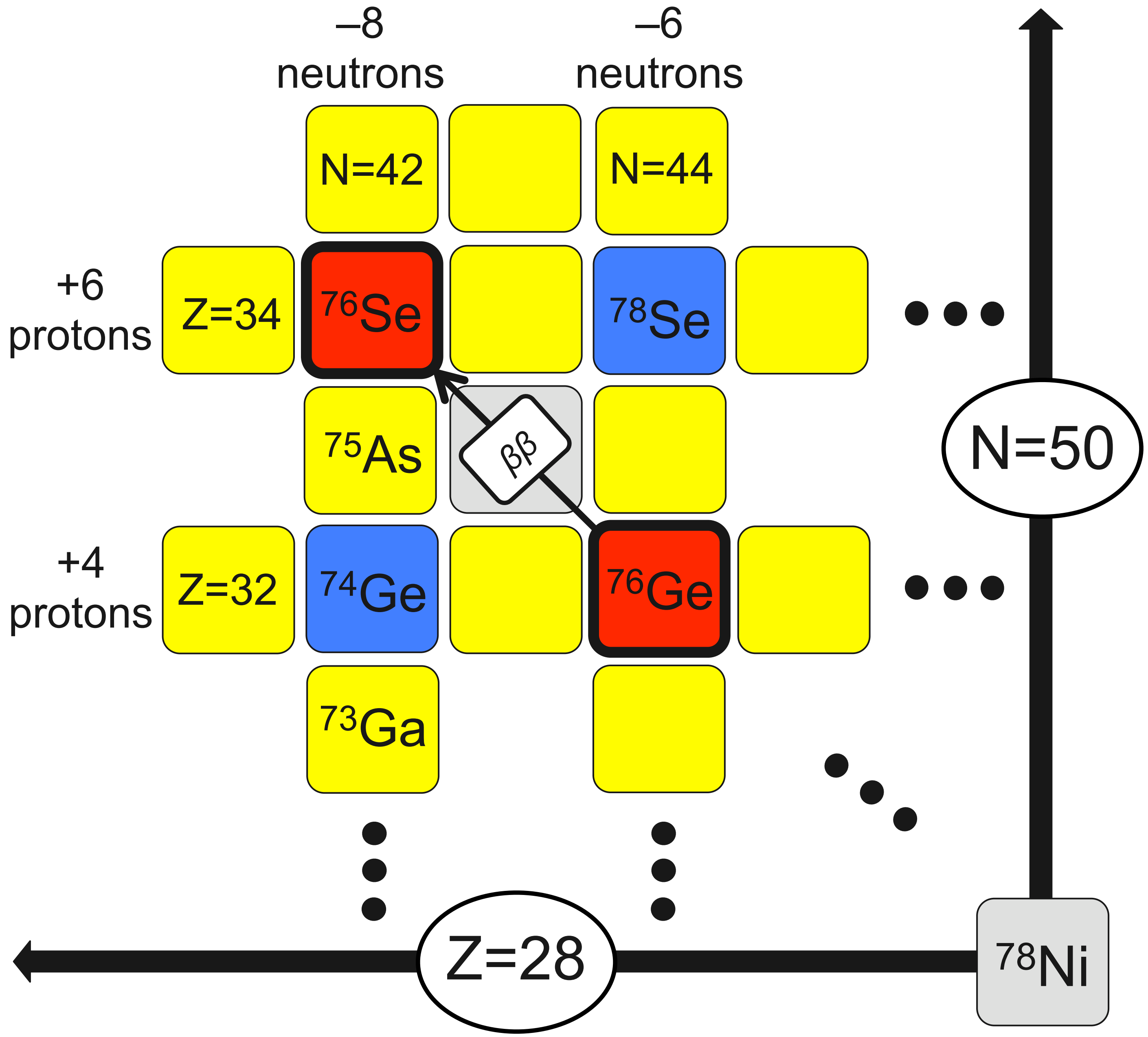
Requires a few steps...

Cartoons courtesy of Peter Mueller, PHY

Nuclear structure – Ge and Se

Shell model of the nucleus
(Nobel Prize for ANL scientist)





Four ‘active’ orbits for Ge and Se

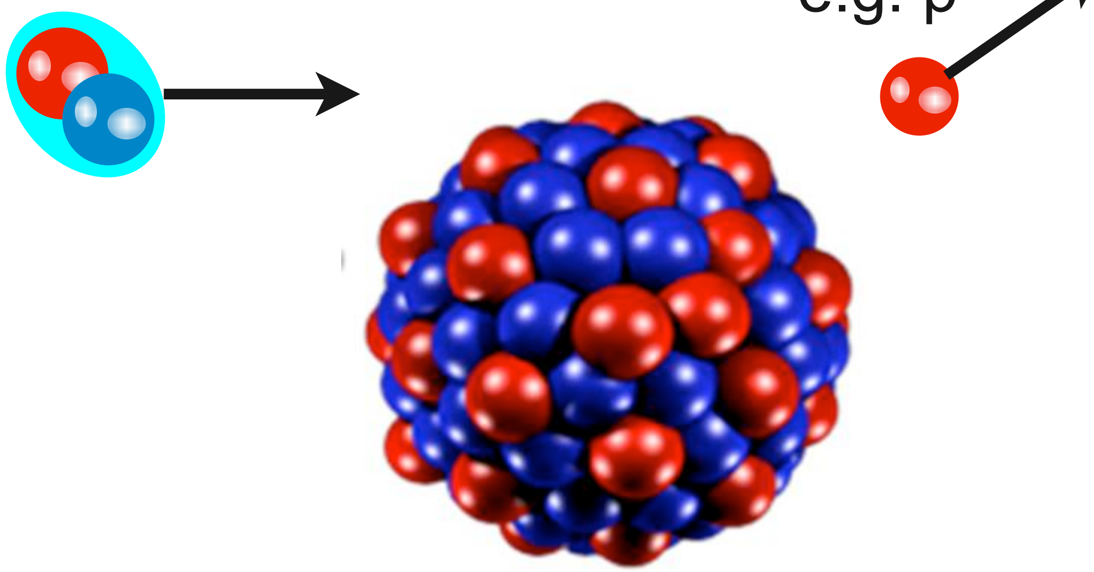
$0g_{9/2}$, $1p_{3/2}$, $1p_{1/2}$, $0f_{5/2}$

$\ell=4$, $\ell=1$, $\ell=1$, $\ell=3$

Step 1: What we can measure

e.g. d

e.g. p



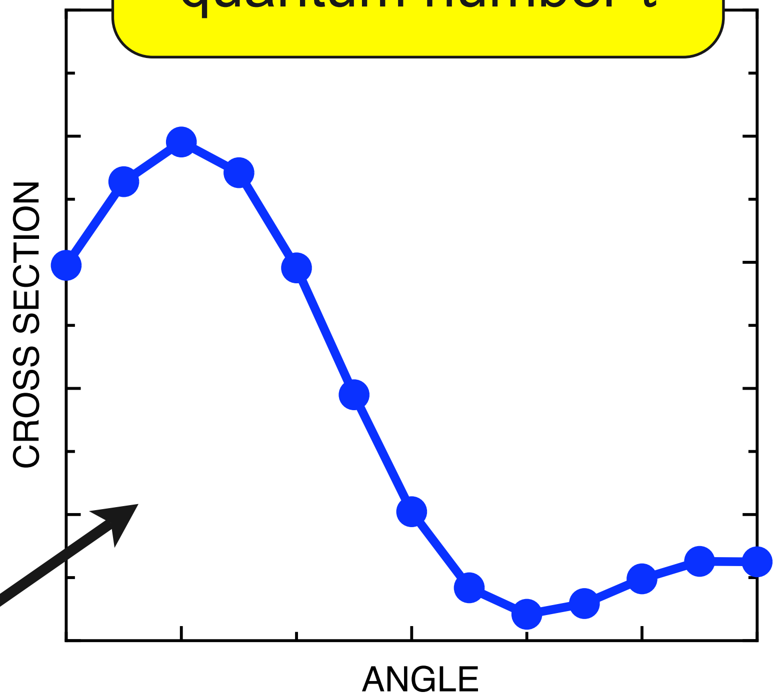
e.g. ^{76}Ge

(Written $^{76}Ge(d,p)^{77}Ge$)

Yield
(Cross section)
Momentum
(Energy)

+

Angular distributions
Gives us the the
quantum number ℓ



The angular momentum 'transferred'

ℓ=4, ℓ=1, ℓ=1, ℓ=3

* If we have performed our experiment appropriately we know the transfer can be considered a one-step process happening dominantly at the nuclear surface, populating single-particle states in the target nucleus…theory follows…

Step 2: 'Spectroscopic factors': a model and an acronym

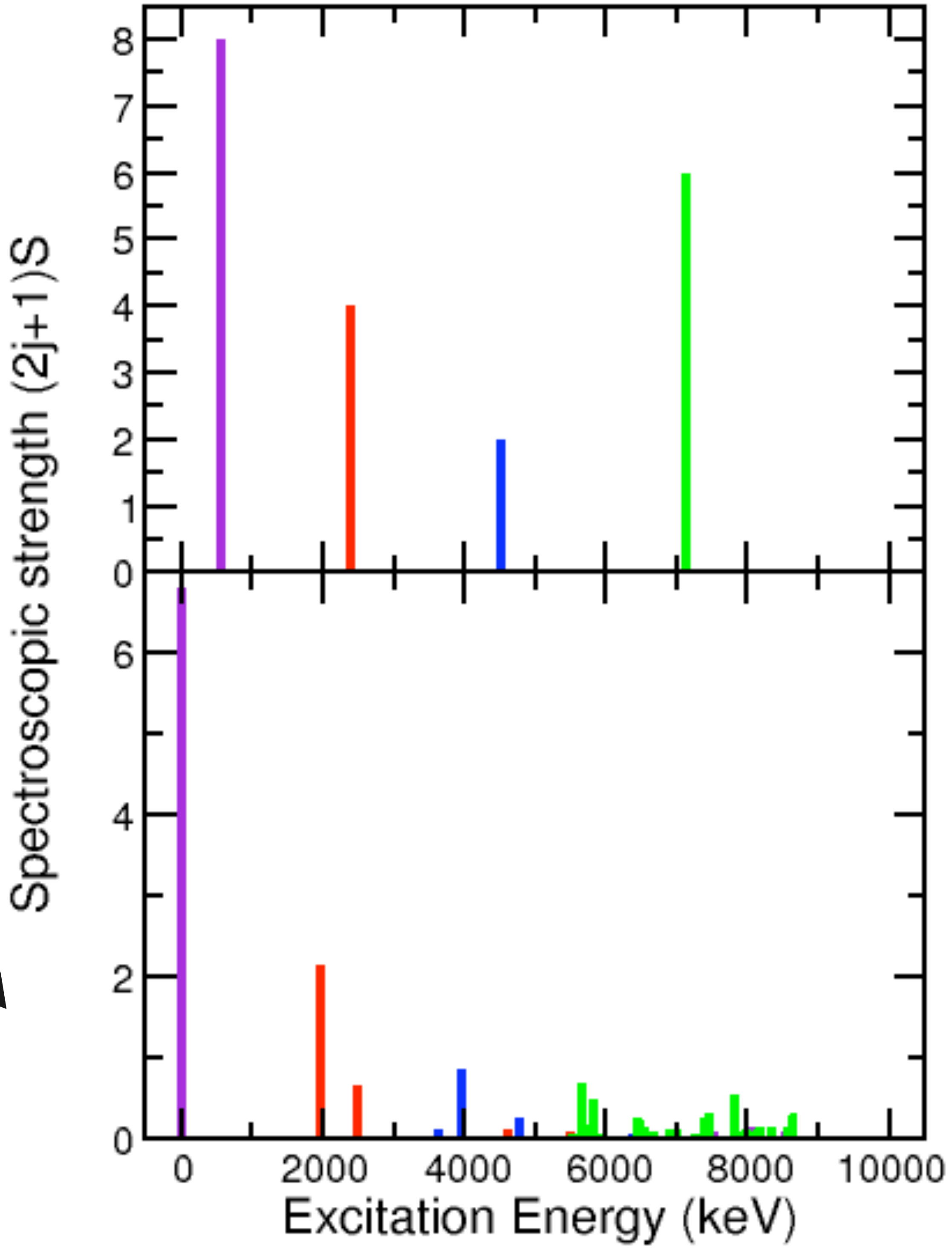
$$\left.\frac{d\sigma}{d\Omega}\right|_{Measured} = gS_{lj}\left.\frac{d\sigma}{d\Omega}\right|_{DWBA}$$

Distorted-wave Born Approximation, calulated cross section

Spectroscopic factor: simply a measure of the overlap between the final state and the initial state plus/minus one nucleon

An ideal shell-model nucleus versus reality

Figure courtesy of S.J. Freeman, Manchester



Step 3: Macfarlane and French sum rules

Number of vacancies = ∑GS(adding)

Number of particles = ∑GS(removing)

- We know S, simply the experimental cross section divided by the calculated cross section
- G hides some details (spins and isospin)
- (2J+1) for adding
- 1 for removing

vacancies + occupancies ⟶ valency of the orbit

REVIEWS OF MODERN PHYSICS VOLUME 32, NUMBER 3 JULY, 1960

Stripping Reactions and the Structure of Light and Intermediate Nuclei*

M. H. MACFARLANE

Argonne National Laboratory, Lemont, Illinois, and University of Rochester, Rochester, New York†

AND

J. B. FRENCH

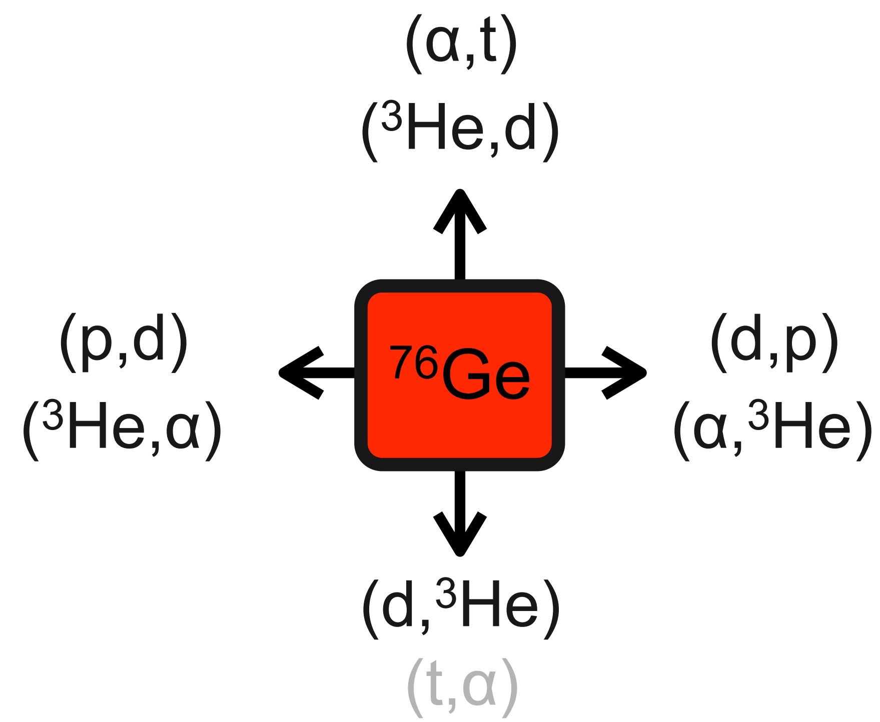
University of Rochester, Rochester, New York

Choosing a reactions, they do different things

Four 'active' orbits for Ge and Se

$0g_{9/2}$, $1p_{3/2}$, $1p_{1/2}$, $0f_{5/2}$

ℓ=4, ℓ=1, ℓ=1, ℓ=3



(From slide 12, remember)

- If we have performed our experiment appropriately we know the transfer can be considered a one-step process happening dominantly at the nuclear surface, populating single-particle states in the target nucleus…theory follows…
- Perform in suitable energy regime: higher energy (e.g. > 6-10 MeV per nucleon) will minimise compound nuclear reactions
- Different reactions favour different angular momentum transfer
- Measure cross sections at, or near, the peak angular distributions

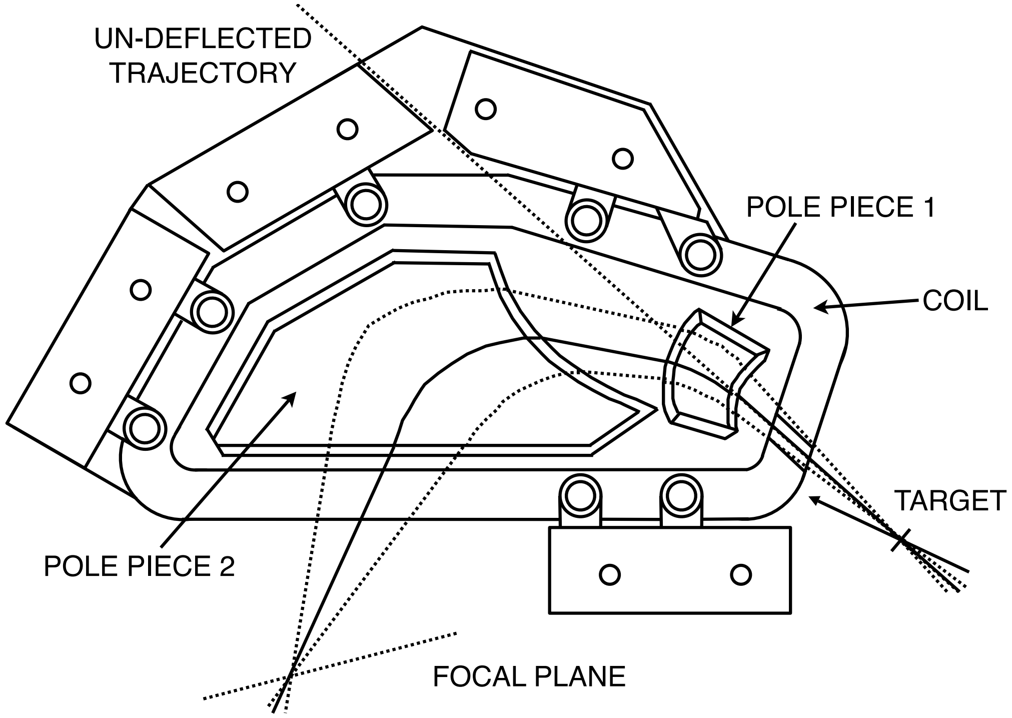
Where do you do this sort of stuff?

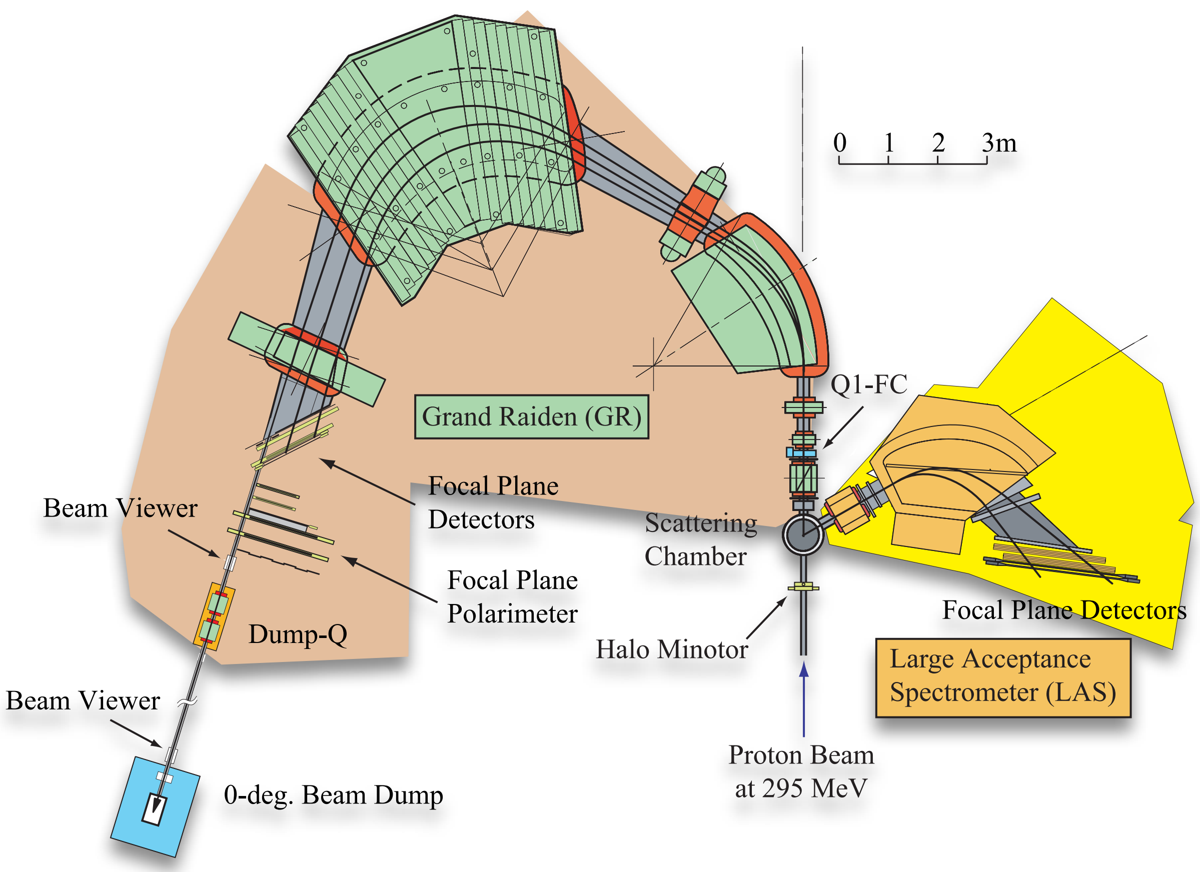
There are now only a few facilities world wide where it is possible to perform these experiments.

As facilities look towards the future, studying nuclei far from beta stability, high-quality beams of protons, deuterons and alpha particles are now rare.

For the neutron work, we chose the Wright Nuclear Structure Laboratory at Yale University, home of an ESTU tandem Van der Graaff accelerator, plus an Enge split-pole spectrograph.

For the proton work, we chose RCNP at Osaka University. Capable of high-energy polarised beams and home to the Grand Raiden spectrometer.





Neutron adding/removing (Yale University)

(p,d) ← ^{76}Ge → (d,p)

(^{3}He,α)   (α,^{3}He)

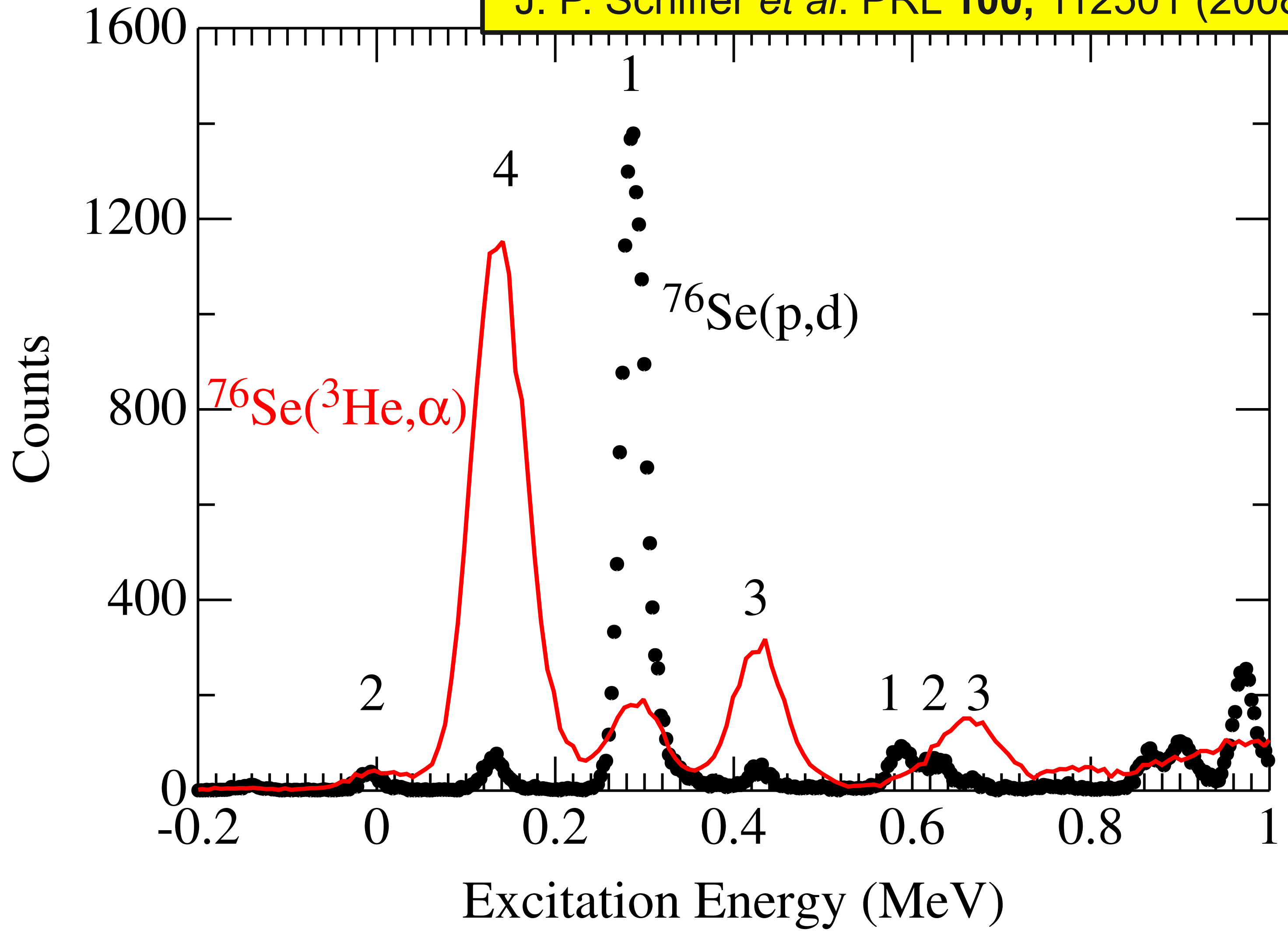
- Performed all these reactions
  - p @ 23 MeV, d @ 15 MeV
  - α @ 40 MeV, ^{3}He @ 26 MeV
- To get absolute cross sections, normalised to a known cross section (Rutherford)
- Measure cross sections a peak yields, determined before hand using DWBA
- Reactions momentum analysed using Yale split-pole spectrograph

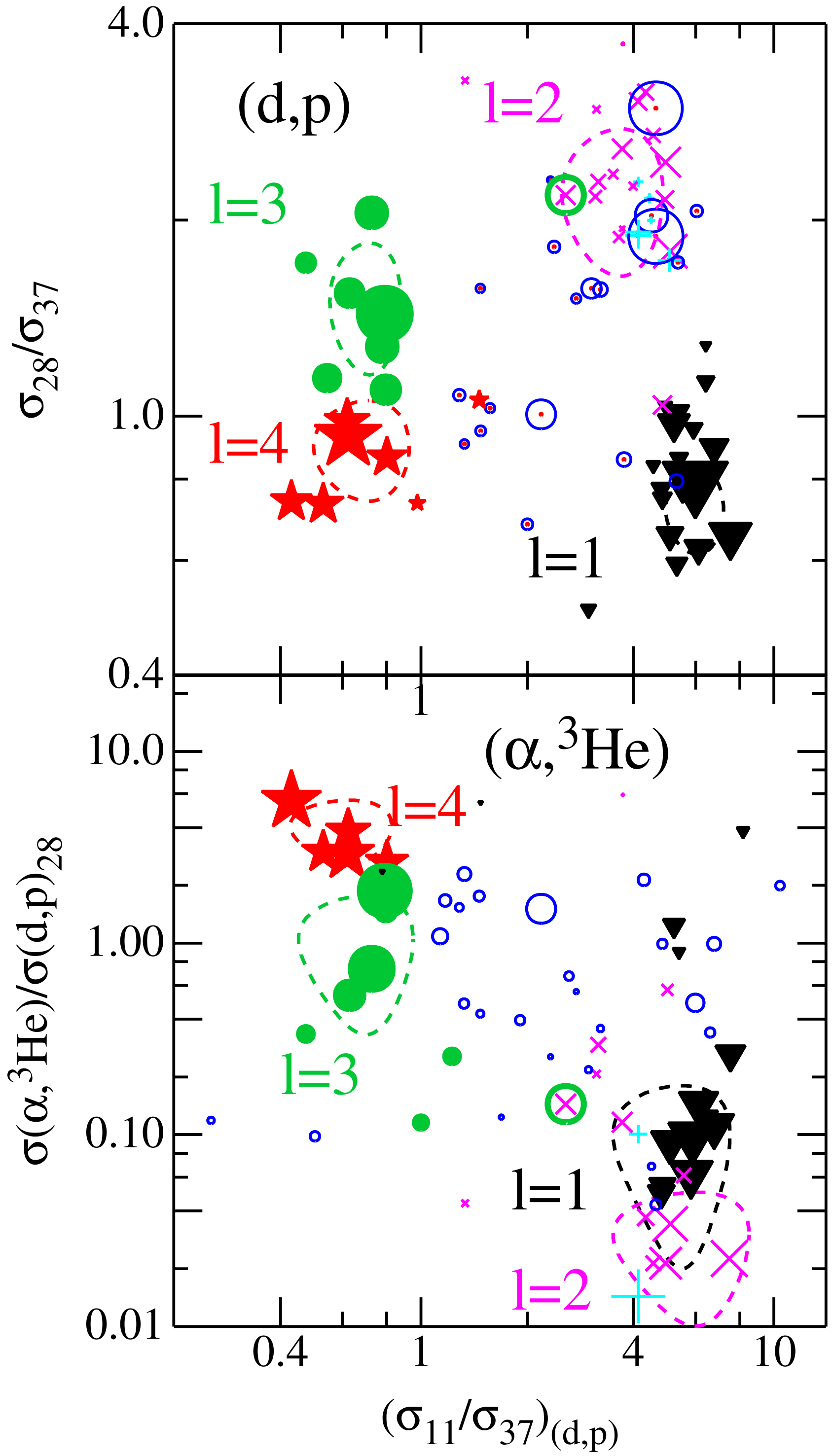
Method

- ***Measure cross sections***
  (STATISTICAL + SYSTEMATIC)
- ***States identified by spin / parity***
  (possible systemtic)
- Do DWBA
  (SYSTEMATIC)
- ***Divide experiment / theory***
- ***Now have absolute spectroscopic factors…these are not too meaningful***
  (SYSTEMTIC)
- ***Use a common normalisation to get relative spectroscopic factors***
  (SYSTEMTIC - reduced)

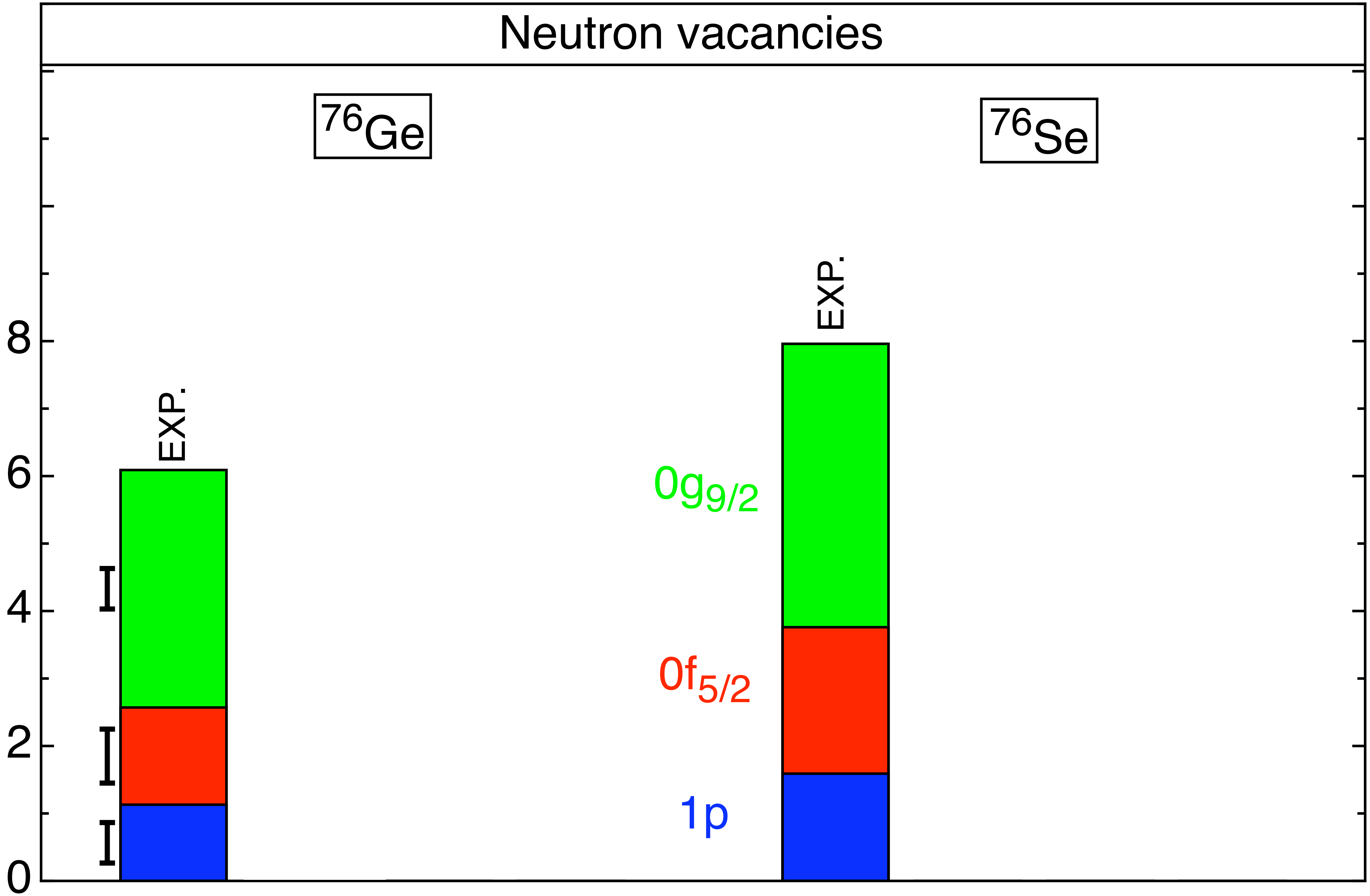
Neutron adding/removing (Yale University)

J. P. Schiffer *et al.* PRL **100,** 112501 (2008)

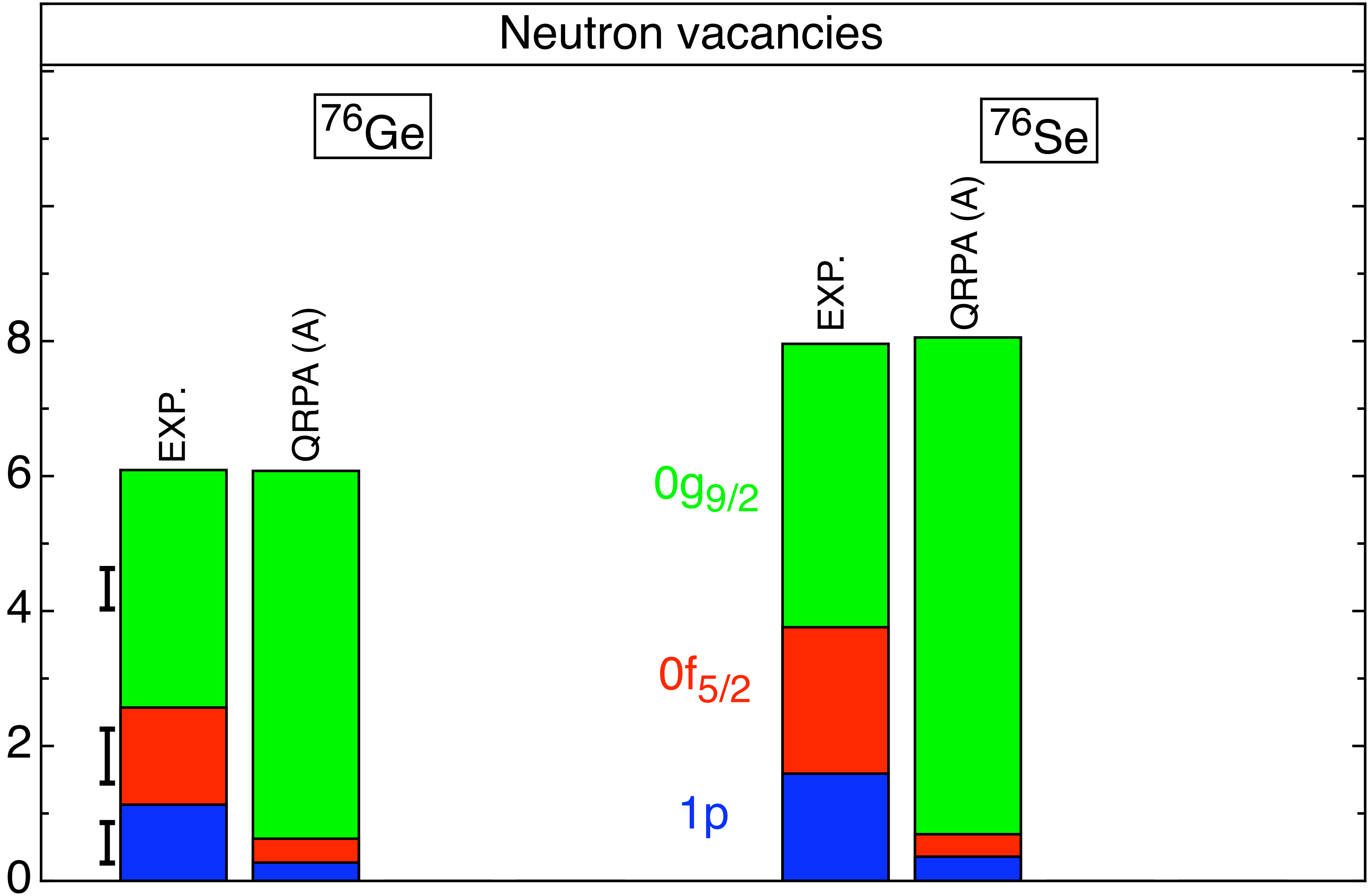




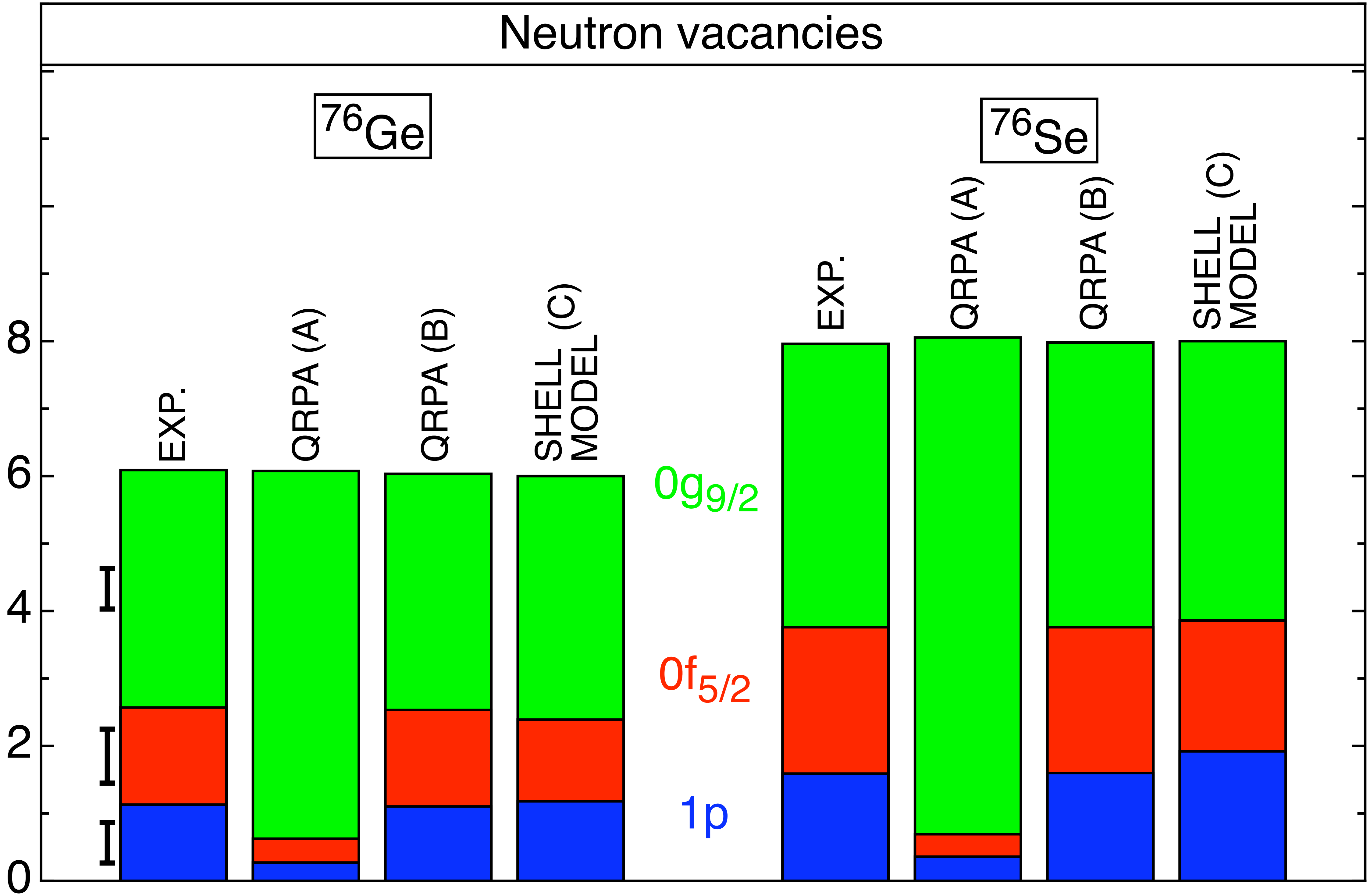
✱ Illustrates the selectivity of these reactions



(EXP.) J.P. Schiffer *et al*. PRL **100,** 112501 (2008)

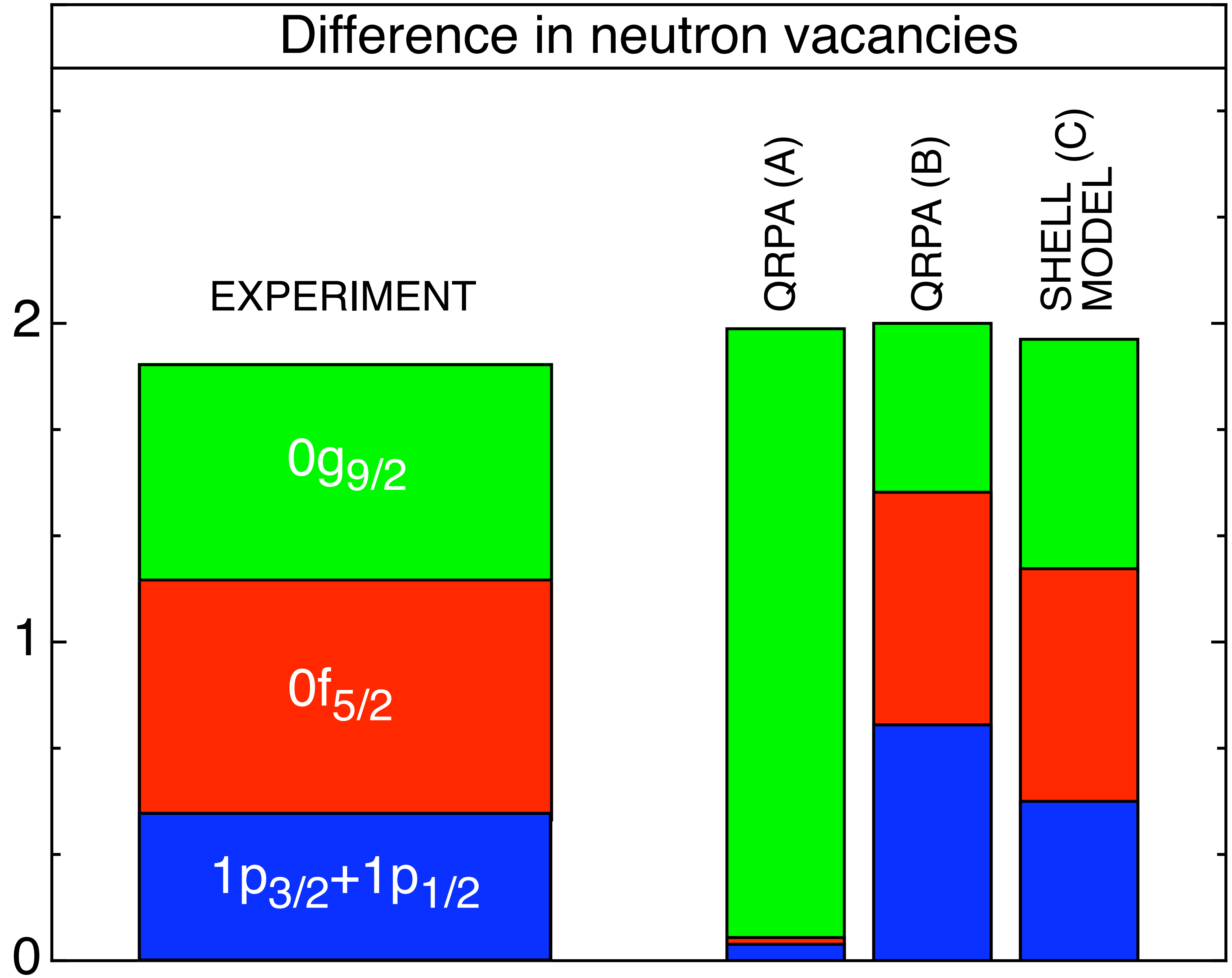


(EXP.) J.P. Schiffer *et al*. PRL **100,** 112501 (2008)
(A) QRPA calculation. Rodin *et al*, private comm. Method see NP **A766**, 107 (2006)



(EXP.) J.P. Schiffer *et al*. PRL **100,** 112501 (2008)
(A) QRPA calculation. Rodin *et al*, private comm. Method see NP **A766**, 107 (2006)
(B) QRPA calculation. Suhonen *et al*, private comm. Method see PLB **668**, 277 (2008)
(C) Shell-model calculation. Caurier *et al*, private comm. Method see PRL **100**, 052503 (2008)

- Using Macfarlane-French sum rules extracted vacancies
- Many consistency check performed in the normalisations
- Neutrons from three orbits are changing substantially between ^{76}Ge and ^{76}Se



(EXP.) J.P. Schiffer *et al*. PRL **100,** 112501 (2008)
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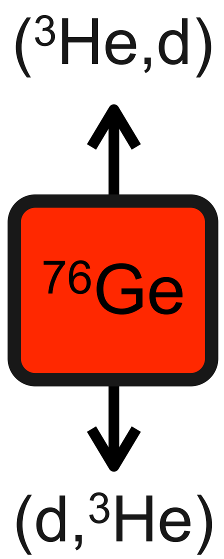
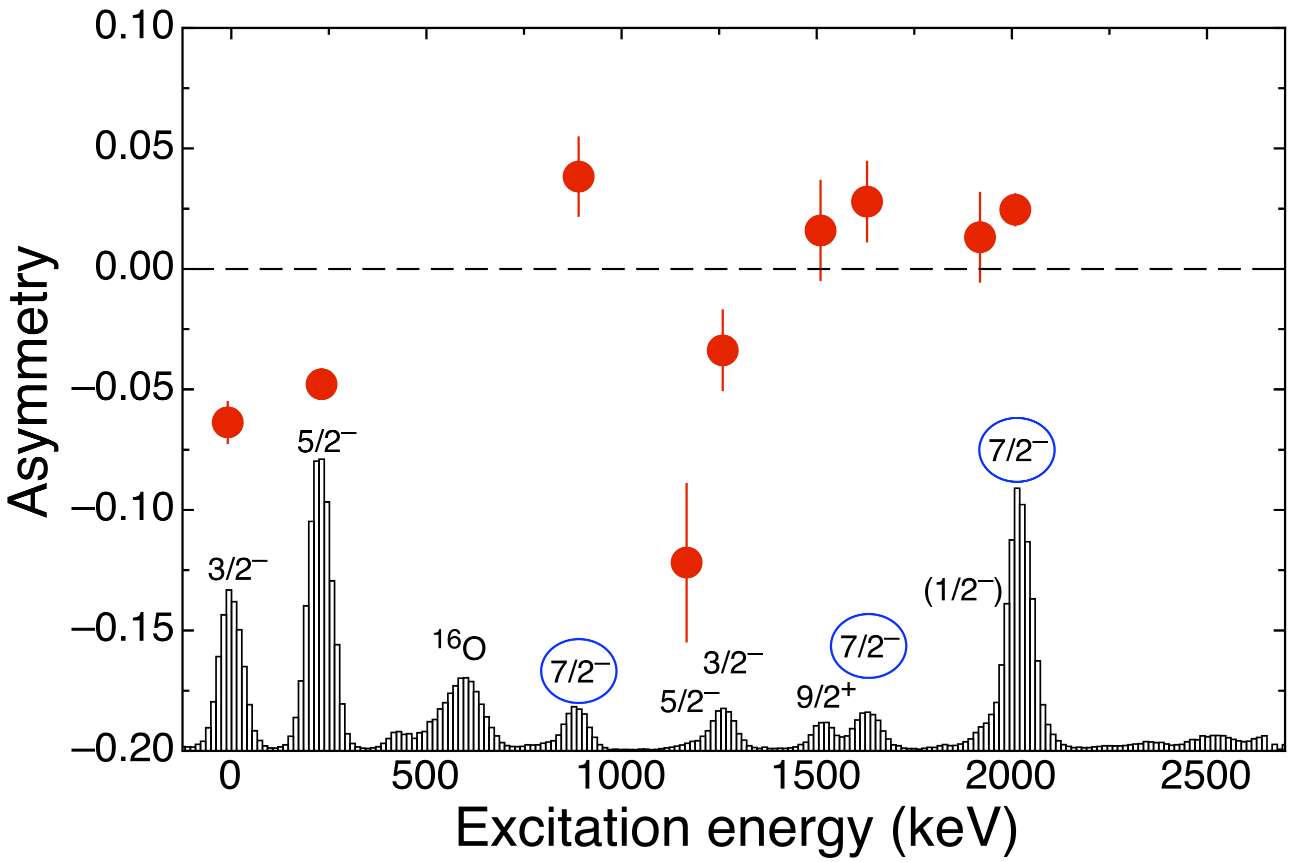
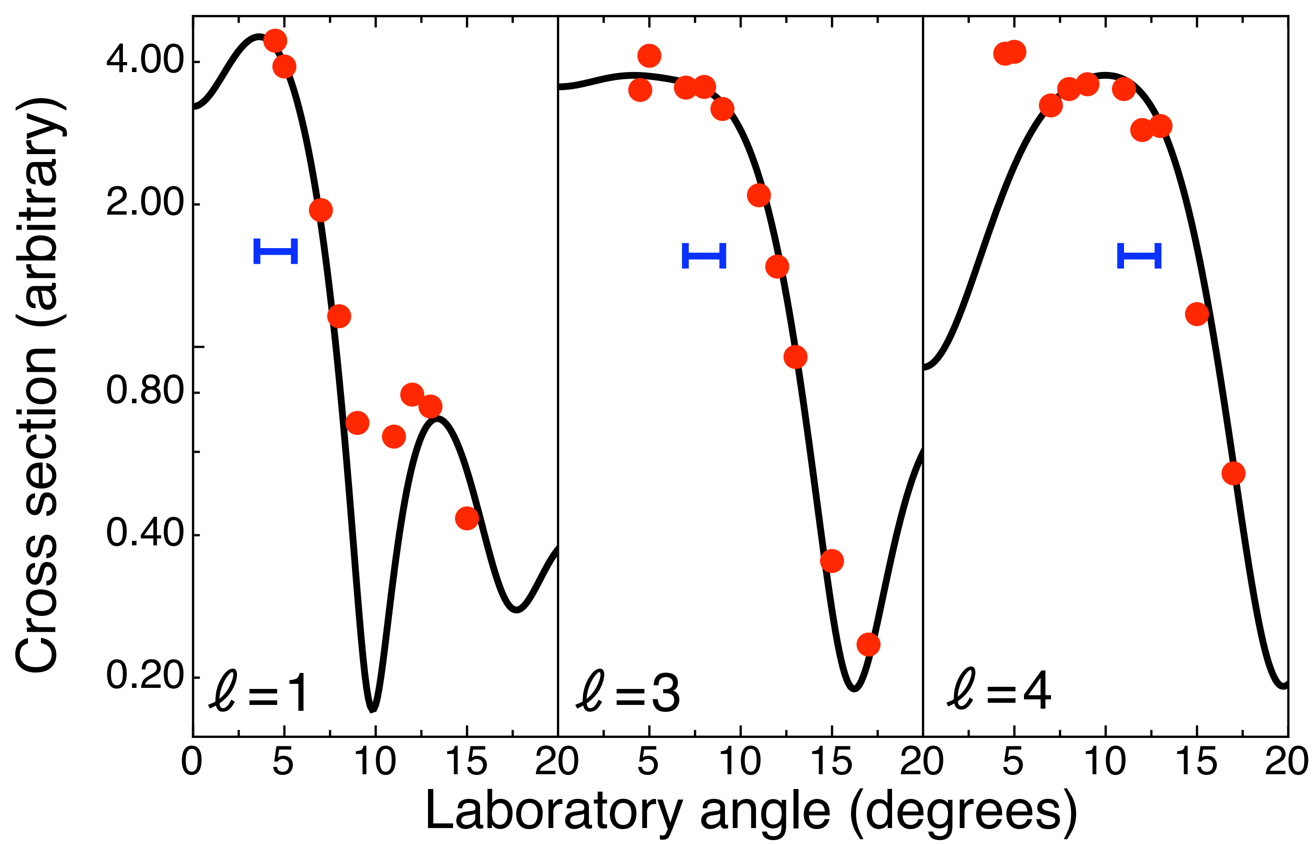
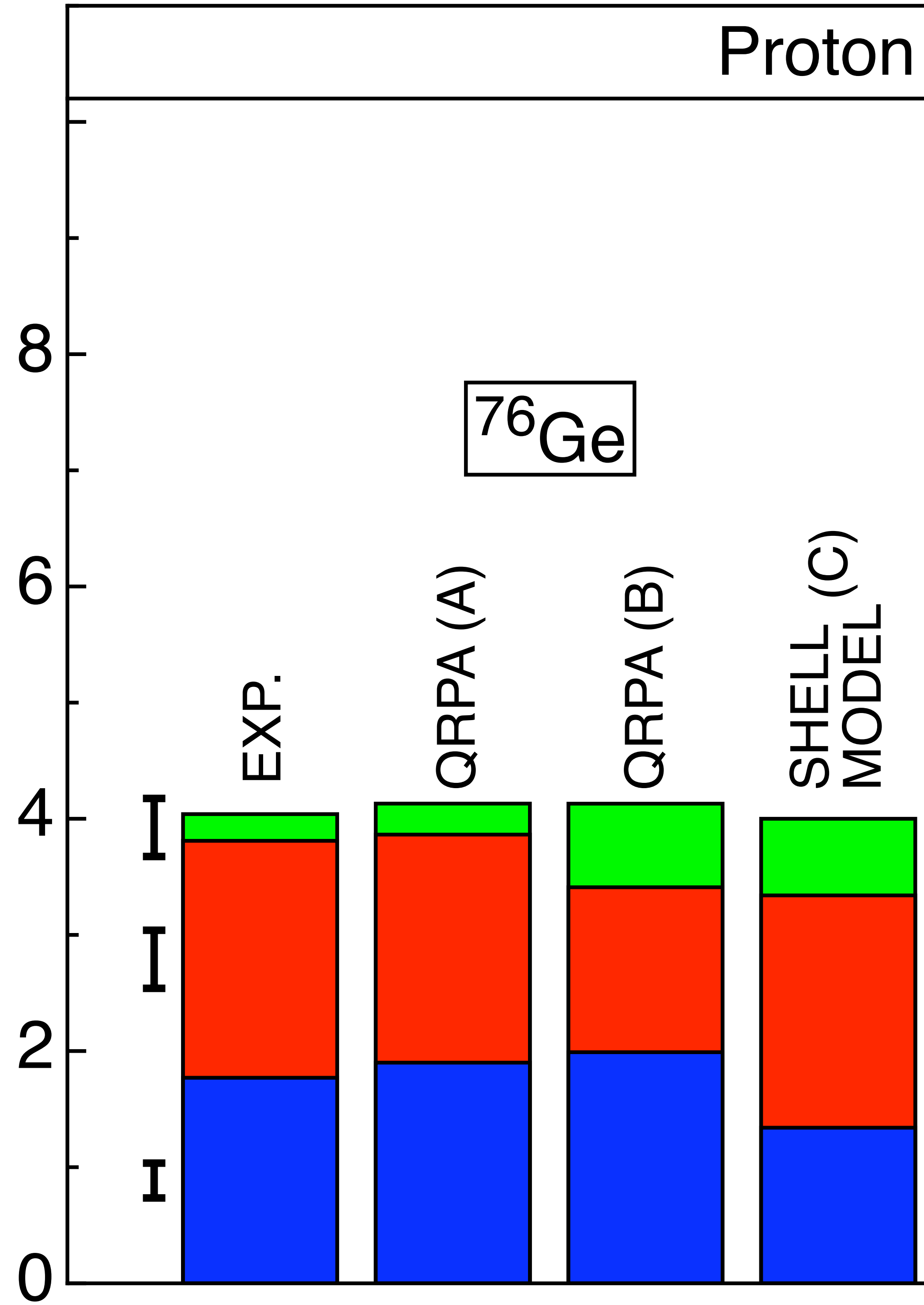
Proton adding/removing (Osaka University)



- Performed all these reactions
  - p @ 23 MeV, d @ 15 MeV
- Method very similar to that used for the neutrons
- Used a polarised beam to assist in the assignment of *j* (data lacking in the literature)







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- (same comments as for the neutrons)
- Using Macfarlane-French sum rules extracted vacancies
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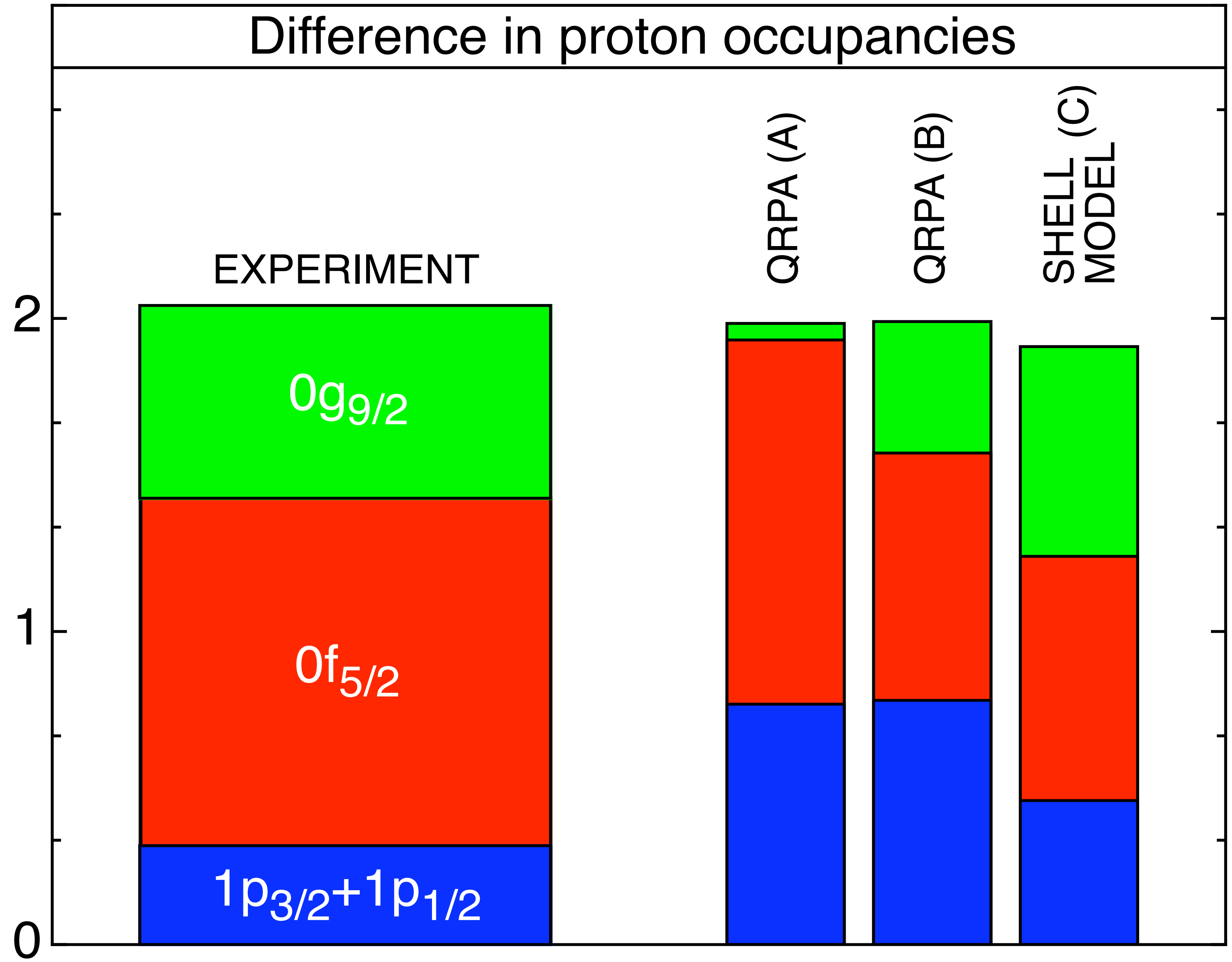

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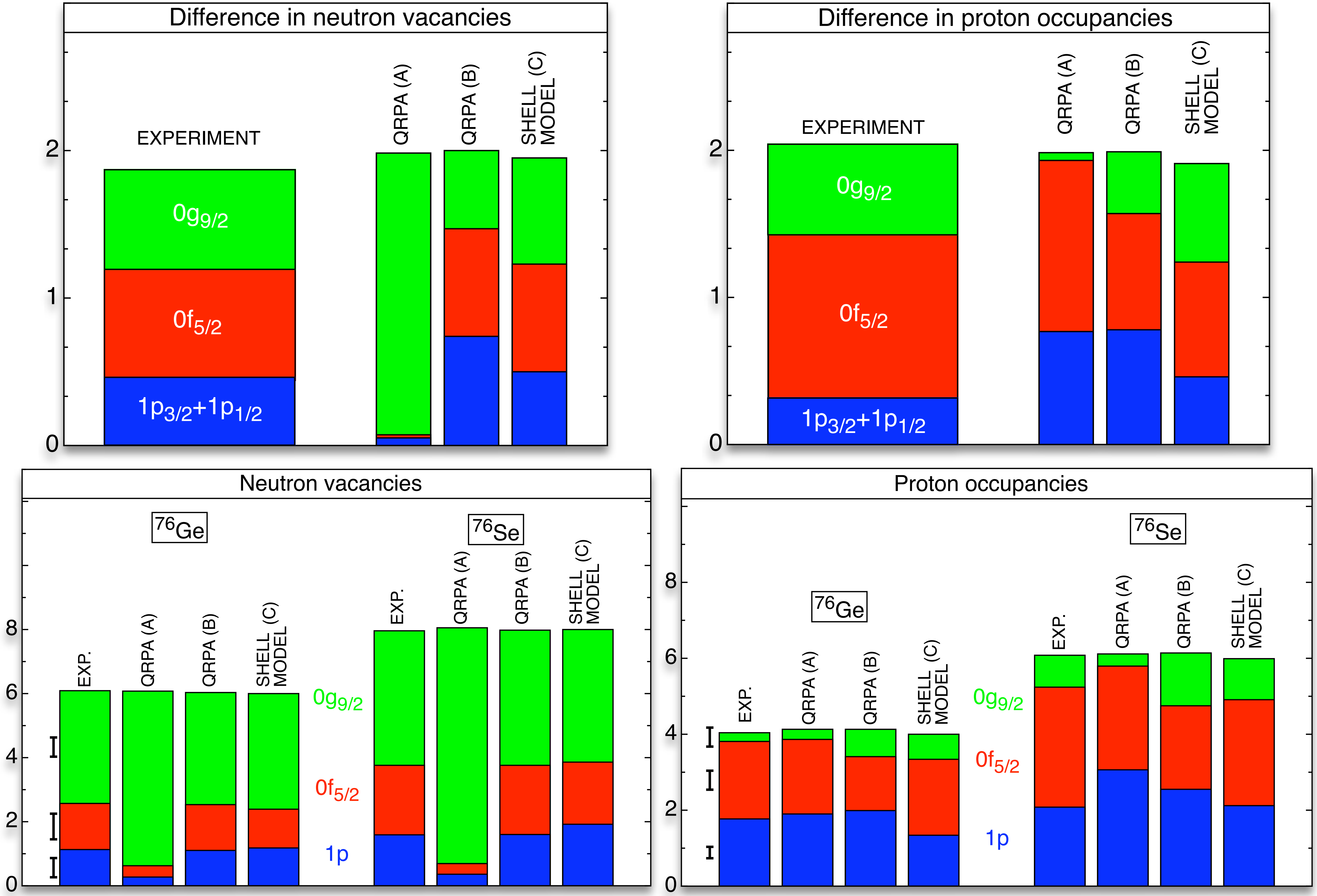
The final picture...



Conclusions

* An attempt to focus the theoretical community by providing possible ingredients for the calculation of the nuclear matrix elements. It is not clear what impact or implication these will have. It should help constrain the models. They have been well received.

* Note there are other considerations e.g. pairing correlations; we have performed the neutron-pair removal reaction on these nuclei, hope to see the proton-pair adding (^{3}He,d) reaction done soon (December 2008).

* The internal consistency of these results perhaps constitutes the most quantitative test of the sum rules in single-nucleon transfer.

* Possible to do for other systems e.g. the ^{130}Te / ^{130}Xe system (Berkley group interested)

- Pairing correlations in ^{76}Ge and ^{76}Se — S.J. Freeman *et al*. PRC **75** 05130(R) (2007)
- Valence neutrons in ^{76}Ge and ^{76}Se — J.P. Schiffer *et al*. PRL **100,** 112501 (2008)
- Valence protons in ^{76}Ge and ^{76}Se — B.P. Kay *et al.* Submitted to PRC(R) 10/22/2008
- See arXiv:0810.4108 [nucl-ex] for preprint
- **ALL** our data are on-line www.nndc.bnl.gov/XUNDL (nearly)